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EOCENE IGNEOUS ROCKS NEAR MONTEREY, VIRGINIA: A FIELD STUDY[1]

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The igneous rocks of Highland County, Virginia have fascinated geologists for over 100 years. The rocks are remarkable by how they contrast with their geological surroundings. Highland County lies within the Valley and Ridge geologic province in western Virginia (Figure 1). The province, once the site of folding and thrusting of sedimentary rocks during the Paleozoic era, is now known for quiet stable geology not for igneous activity.

These igneous rocks are found over a widespread area that tends to concentrate around two centers: near Trimble Knob in Highland County, and near Ugly Mountain, in southern Pendleton County, West Virginia. An exception to this pattern is an isolated occurrence at Mole Hill in Rockingham County, Virginia. The rocks form a variety of igneous

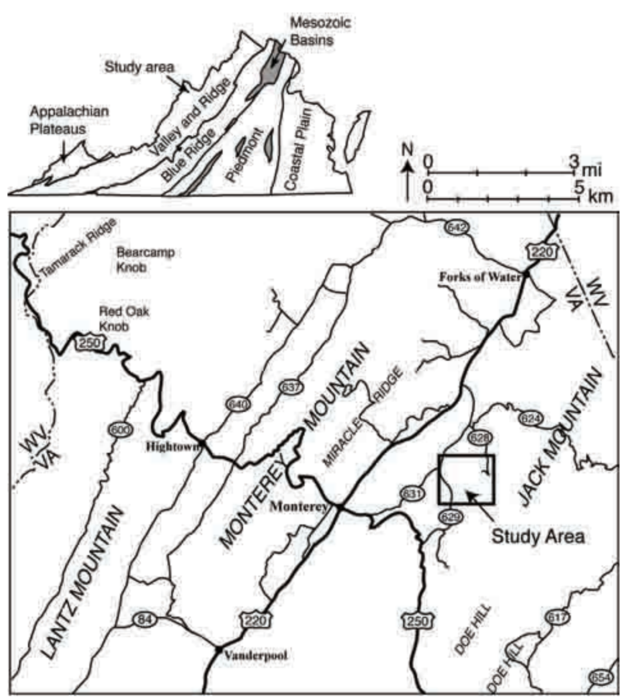

Figure 1. Location of the study area within the geologic provinces of Virginia (top) and with respect to the major roads and topographic features in the region (bottom).

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bodies, ranging from dikes and sills, only a half meter or so wide, to larger bodies of more circular shape such as Trimble Knob, with a diameter of approximately 150 meters (Rader and others, 1986). Presumably, the dikes and sills represent the old plumbing system that once fed a volcanic complex that has since been eroded away. The larger bodies such as Trimble Knob and Ugly Mountain may represent old volcanic necks or pipes.

Many of the bodies, particularly ones that crop out along roads, in quarries, or have an obvious topographic expression, have been mapped and studied (Garner, 1956; Kettran, 1970, Johnson and others, 1971). A striking aspect of the dikes and sills is their compositional range, which stretches from mafic through felsic. These rocks are predominantly aphanitic, commonly porphyritic, and occasionally vesicular. An important, although less common rock type, is "volcanic breccia" or "diatreme". This rock contains millimeter-to-centimeter-scale clasts of igneous rocks of varied compositions, of sedimentary country rocks, and individual crystal grains of olivine, clinopyroxene, hornblende, and biotite, embedded in a fine, highly-altered matrix.

Prior to 1969, it was assumed that the most likely age of these rocks was Mesozoic. Mesozoic igneous rocks, mostly in the form of mafic dikes, are common throughout the Blue Ridge and Piedmont provinces, and are associated with Atlantic rifting during the breakup of Pangea. It was previously thought that the Highland County rocks are merely an extreme western extension of this belt. However, during a study to determine if some of the igneous rocks are related to the Devonian Tioga bentonite, Fullagar and Bottino, 1969, using K-Ar, and Rb-Sr isotopic techniques, came to the surprising conclusion that the rocks are a much younger Eocene age of approximately 47 Ma. This Eocene age is quite significant, because that makes the igneous rocks of Highland County the youngest igneous rocks known in the eastern United States.

This discovery sparked intense study and speculation about the origin of the rocks. Southworth and others, 1993, employing isotopic and geochemical methods, undertook a comprehensive study sampling both Eocene and Mesozoic igneous rocks over a wide area in Highland, Rockingham, and Pendleton counties. They came to the following conclusions: 1) the Eocene rocks cover a broad chemical range from mafic (basalt, picrobasalt, and basanite) through felsic (trachyte and rhyolite) with concentrations at the mafic and felsic ends and relatively few intermediates; 2) radiometric dates combined with paleomagnetic dates are consistently middle Eocene at approximately 48 Ma; 3) the igneous activity was rather short-lived – perhaps a few million years; 4) isotopic evidence does not indicate significant crustal contamination, so that after the magmas were generated in the mantle, the magmas moved rapidly upward with relatively little interaction with the country rock; and 5) chemical plots of major and minor elements indicate that the mafic and felsic rocks had a common source and their tectonic environment was consistent with within-plate continental extension. Of note was the discovery that not all the igneous rocks in Highland and Pendleton Counties are Eocene. A sample of mica pyroxenite from Pendleton County was dated at 148 Ma.

The cause of the igneous activity in an otherwise quiet geological area is not known, but it is the subject of much debate. Theories include: 1) a regional basement fracture zone, the 38th parallel lineament, has provided a focus for igneous activity (Fullagar and Bottino, 1969 and Dennison and Johnson, 1971); 2) a still-cooling intrusion is responsible for the regional uplift of the "Virginia Highlands" and the nearby hot springs of Bath County (Dennison and Johnson, 1971); 3) a global shift in plate tectonic motion occurred in the Eocene. This shift resulted in the formation of the Bermuda Rise and was also responsible for igneous activity as far inland as Highland County (Vogt, 1991); 4) the transition between thin Atlantic lithosphere and thick North American lithosphere created a small scale downwelling convection current, and that the Eocene igneous activity was a result of an upwelling return flow (Gittings and Furman, 2001 and King and Ritsema, 2000). Southworth and others, 1993, summarized the merits of many of the theories and concluded that a combination of causes (a reactivation of basement fracture zones and a plate-tectonically driven extension of North America, possibly associated with plate tectonic direction shift in the Eocene) provided the right conditions to form magma.

The purpose of this study is to observe how the surrounding bedrock structure helped to guide the ascent of the magma; to study how the mafic rock, felsic rock, and breccia relate to each other; and to determine the origin of the breccia. Preliminary mapping by the Virginia Division of Mineral Resources indicated that a small area 3.5 km east of Monterey would be suitable for this study. The area contains an unusually high concentration of the three main igneous rocks, the exposure is reasonably good for this region, and the area yields relatively fresh samples. As a part of a larger mapping study that included this locality, Kettran, 1970, also found a high concentration of bodies in this area. The area was also featured at stop nine in Johnson and others, 1971. More recently, the study area was featured in two field trip guidebooks (stop six of Tso and others, 2003; and stop three of Tso and others, 2004). Close field observation, thin section study, and structural and geochemical study were employed to bring together a sense of the emplacement mechanism and volcanic history.

STUDY AREA

The study area, located 3.5 km east of Monterey within the Monterey quadrangle, can be accessed from State Roads 628, 629, and 631 and numerous farm roads (Figure 1). The approximately 2.5-square-kilometer area is primarily pastureland with scattered stands of trees. Good outcrop may be found along Strait Creek near State Road 629 and in other creeks in the southwest part of the area. There is considerable vegetative cover over much of the study area, so observing widely scattered outcrops and float was important during mapping. Many of the igneous bodies were identified by observing areas containing igneous float and lacking sedimentary float. Soil cover made it difficult to precisely determine the boundaries of the bodies, and contact relations with the surrounding rock were only rarely observed. In places where we found intermixed igneous and sedimentary float without clear contacts, we chose to map the whole occurrence as "igneous and sedimentary rock". In several cases, dike-like shapes were inferred from the linear trend of isolated outcrops. Many isolated smaller bodies were mapped as having a circular or oval shape based on single outcrops and patches of float, but the true shapes of these bodies are unknown. Although several dike-like bodies were observed in roadcuts or quarry walls, attempts to trace them away from where they were exposed were unsuccessful. Larger breccia bodies and nearby igneous rocks form small knobs or ridges. The smaller dikes, however, do not have obvious topographic expression. The mapping done for this study agrees well with that of Kettran, 1970, and mapping by the Virginia Division of Mineral Resources (Rader and Wilkes, 2001).

SURROUNDING BEDROCK GEOLOGY

Highland County hosts sedimentary rocks of Ordovician to Mississippian age (Figure 2). Regionally, the igneous bodies are observed to intrude rocks from the Ordovician Beekmantown Formation through the Devonian Foreknobs Formation (Garner, 1956). Broad anticlines and synclines dominate the regional geological structure, with Ordovician rocks found in the cores of the anticlines (the Hightown and Bolar Anticlines being the most prominent) and Devonian rocks found in the cores of synclines.

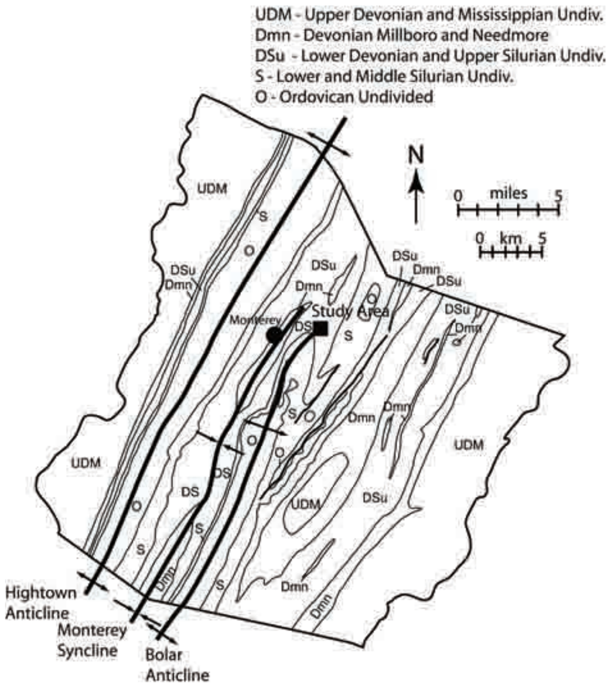

Figure 2. Generalized geologic map of Highland County, based on Virginia Division of Mineral Resources, 1993, Rader and others, 1986, and Rader and Wilkes, 2001.

The regional strike trends northeast-southwest giving Highland County a strong structural and topographic grain in those directions.

The study area is underlain by upper Silurian rocks (McKenzie Formation, Williamsport Sandstone, Wills Creek Formation, and Tonoloway Formation, Table 1). The Williamsport Sandstone serves as the main stratigraphic mapping horizon (Figure 3). It forms two outcrop bands: a looping band on the west side of the study area that follows the closure of the Bolar Anticline, and an eastern band that trends northeast. Between the two sandstone bands, in the center of the study area, the thinly bedded shaly limestones of the Wills Creek and Tonoloway Formations form the core of a complex syncline. Here, strikes maintain a general northeast direction, although dip angles and directions can vary widely. This indicates that the relatively soft Wills Creek and Tonoloway Formations are folded into many smaller folds on the scale of tens of meters. Because of possible stratigraphic repetition, poor exposure, and lithologic similarities, no attempt was made to differentiate between the Wills Creek and Tonoloway Formations. The complex structure creates a repetition of the sandstone layers of the Williamsport and Wills Creek, causing sandstone boulder-strewn fields over much of the pastureland that is underlain by these formations.

Formation	Lithology	Reference
Tonoloway Limestone	Thinly laminated dark gray to black platy limestone; interbedded 1-2 cm thick limestone, bluish gray in places, somewhat more resistant than Wills Creek	Woodward, 1941; Butts, 1940
Wills Creek Formation	Finely laminated dark to medium gray fine-grained limestone and interbedded 0.5 to 1 meter thick limestone, calcareous shale, rare thin sandstones, poorly exposed.	Woodward, 1941; Butts, 1940
Williamsport Sandstone	Fine to medium grained white orthoquartzite to subarkose, 0.3 to 1 meter beds, interbedded dark gray shales, may exhibit fucoids on weathering surfaces, commonly forms float	Woodward, 1941;
McKenzie Formation	Dark gray thin bedded fissile shale, weathers brown to tan, ferruginous sandstone in 4-10 cm beds, interbedded fine to medium grained dark gray limestone, weathers easily, crops out poorly	Woodward, 1941; Butts, 1940

Table 1. Sedimentary bedrock of the study area.

Joint data was collected on the outcrops within the study area and along the main roads nearby (Figure 4). Joint strikes show two very strong directions: in the cross-strike direction of N40°-60°W, and in the direction of N60°-80°E. Note that this latter joint direction is not parallel to the overall strike of the bedding (which

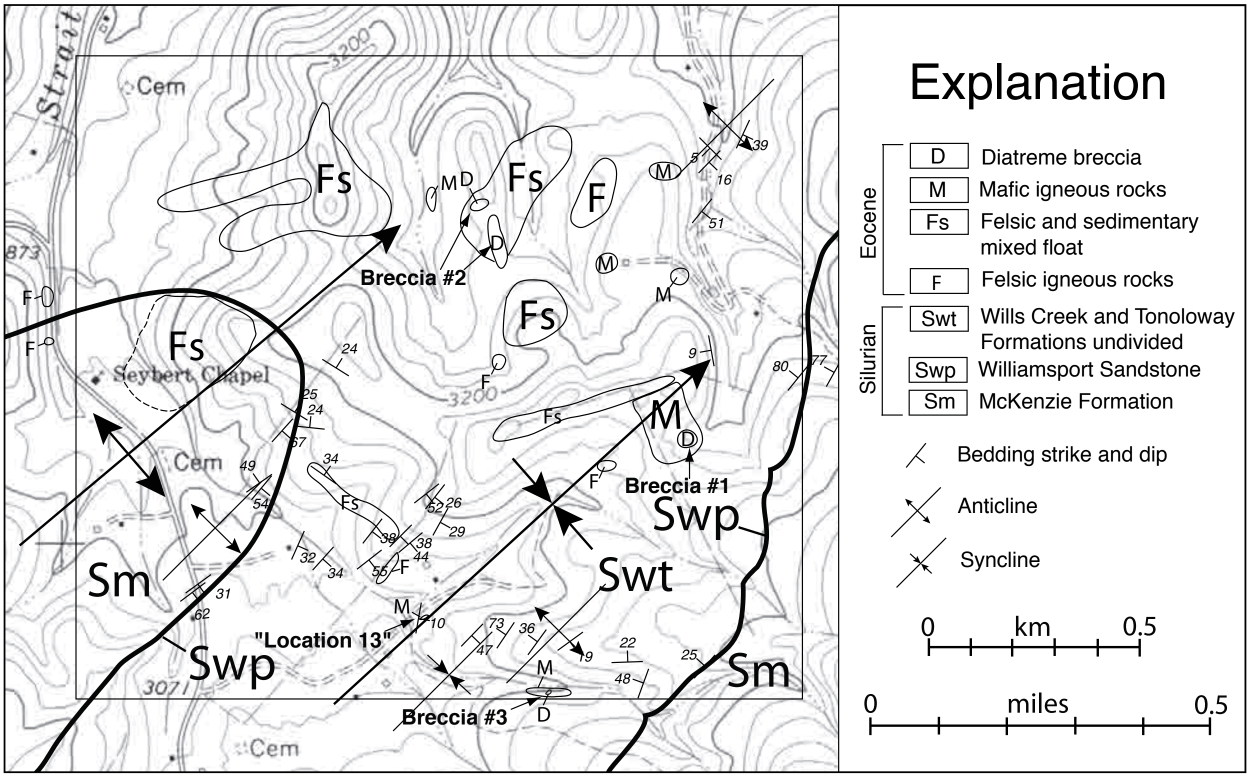

Figure 3. Bedrock geology of the study area.

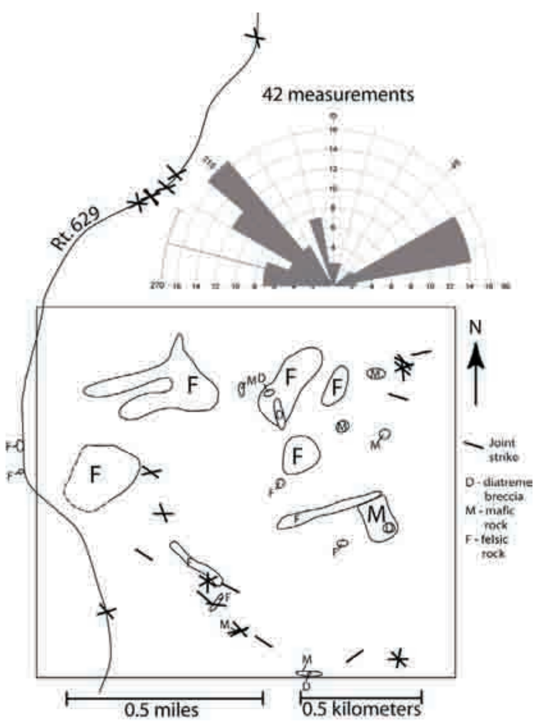

Figure 4. Rose diagrams of joints (top) and map of joint measurements (bottom) in the study area and along major nearby road.

is approximately N45°E). Within the study area, there is only one instance where exposure is good enough to show a good dike-joint relationship. This occurs at "Location 13" (Figure 3), where a mafic dike has intruded into the Tonoloway Formation along a joint set which trends N78°E (Figure 5). Elsewhere, the trends of the dikes can be inferred from the geologic map. Inspection of Figure 4 reveals that all the prominent linear igneous bodies in the study area follow the dominant joint sets. Several felsic bodies have linear trends that parallel the northeast joint direction, and there is one prominent felsic dike that parallels the northwest joint direction.

APHANITIC TO PORPHYRITIC IGNEOUS ROCKS

Rocks collected for thin section study and geochemical analysis are fairly diverse in

Figure 5. Mafic dike is parallel to a major joint set which trends N78E.

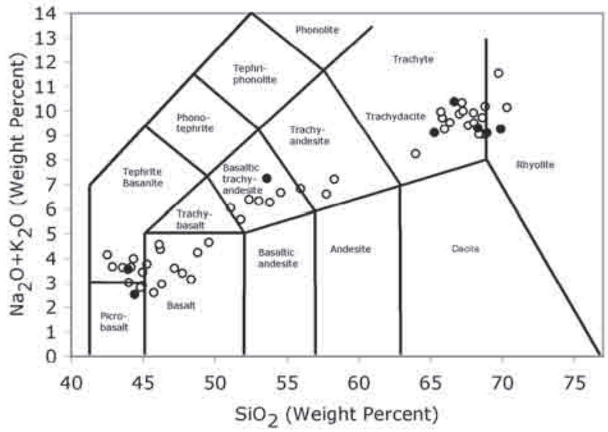

Figure 6. Major element chemical classification based on $Na_2O + K_2O$ against SiO_2 based on the method of Le Bas and others, 1986. The closed circles represent data from this study and the open circles are from Southworth and others, 1993.

terms of composition and texture and were selected to represent the range of lithologies. Major element chemical analyses are presented in Table 2 and compositions of non-breccias are plotted in Figure 6 along with the data of Southworth and others, 1993. The data indicates that the rocks have an alkalic trend, and that they

SAMPLE	**R-1**	**R-2**	**R-3**	**R-6**	**R-12**	**R-12C**	**R-24**	**R-28**	**R-31**	**R-38B**
	Mafic breccia	Aphan. Mafic	Inter-med.	Olivine mafic	Felsic breccia	Felsic	Felsic	Felsic	Felsic	Felsic
Al_2O_3	13.75	16.36	17.55	12.91	15.22	17.64	16.31	15.90	15.73	15.05
CaO	8.40	11.19	6.42	12.76	2.96	2.60	1.17	1.10	1.31	2.69
"Fe2O3" raw number	13.07	12.69	8.74	12.47	6.35	3.52	3.99	2.45	3.27	2.70
FeO*	7.96	7.74	4.37	7.79	2.91	1.49	1.56	0.99	1.36	1.12
Fe_2O_3*	4.22	4.09	3.89	3.81	3.12	1.87	2.26	1.34	1.76	1.46
H_2O	9.85	2.33	2.57	3.12	4.60	1.57	0.89	2.26	2.81	3.68
K_2O	1.34	0.72	2.80	0.83	3.69	4.09	4.52	4.15	4.00	5.23
MgO	6.55	6.62	2.78	10.65	1.46	0.28	0.28	0.30	0.40	0.47
MnO	0.183	0.183	0.213	0.176	0.139	0.119	0.066	0.031	0.033	0.068
Na_2O	2.21	2.69	4.26	1.62	4.15	4.75	5.61	4.77	4.72	3.65
P_2O_5	0.55	0.41	0.72	0.40	0.28	0.20	0.22	0.09	0.08	0.14
SiO_2	41.67	42.22	52.28	43.22	59.13	63.35	65.07	67.31	66.08	65.15
TiO_2	2.069	2.923	1.723	2.301	0.738	0.484	0.382	0.211	0.239	0.221
TOTAL	98.76	97.47	99.57	99.59	98.39	98.44	98.33	98.46	98.52	98.92

Table 2. Major element chemical analyses. Whole rock analyses were performed by Activation Laboratories using a lithium metaborate/tetraborate fusion -inductively coupled plasma technique. * Total iron was analyzed as Fe_2O_3 and was recalculated for FeO/Fe_2O_3 using method of LeMaitre (1976).

form principally in two groups (mafic and felsic) with fewer samples in between the extremes. Other geochemical studies include Hall, 1975, and more recently Gittings and Furman, 2001, and Diecchio and others, 2001.

Mafic Rocks

Mafic rocks are characteristically dark gray to black in color. They range from aphanitic to aphanitic-porphyritic with phenocrysts that include plagioclase, clinopyroxene, and occasionally olivine (Figure 7). Matrix minerals include abundant thin laths of plagioclase, opaque (magnetite) and clinopyroxene. Some rocks show a parallel alignment of matrix plagioclase indicating a flow texture. Amygdules may also be present, with zeolite and calcite the principal minerals filling the cavities.

Felsic Rocks

Compared to mafic rocks, the felsic rocks are more mineralogically variable and texturally complex and provide more details of their eruptive history. As a group, they stand out from the mafic rocks by their light-to medium-gray color when fresh and weather to a buff to pink color. The most abundant mineral in all felsic rocks is plagioclase which comprises 80-95% of the rock and usually, with the exception of a small percentage of fine opaque, comprises nearly all the aphanitic matrix. Matrix textures commonly show parallel alignments of plagioclase laths. Most felsic rocks are porphyritic with phenocrysts that include: plagioclase (most common), biotite, hornblende, orthopyroxene (rare), and orthoclase (rare) (Figure 8). Amygdules are observed in felsic rocks as well but less commonly than in mafic rocks. One sample contains microphenocrysts of quartz.

Felsic rocks can show textural complexity. Near breccia body Number 2 (Figure 3), felsic rock contains inclusions of previously formed felsic rock, seen as parallel streamlined lenses on the centimeter scale (Figure 9). In thin section, the inclusions are observed as elliptical areas showing internal flow banding in orientations slightly different from the flow banding of the matrix. Felsic rocks may contain xenoliths of sedimentary country rock. Rocks with such xenoliths contain a finer grained matrix than other felsic rocks, indicating that they cooled more quickly and probably formed near the margin of the body next to the country rock.

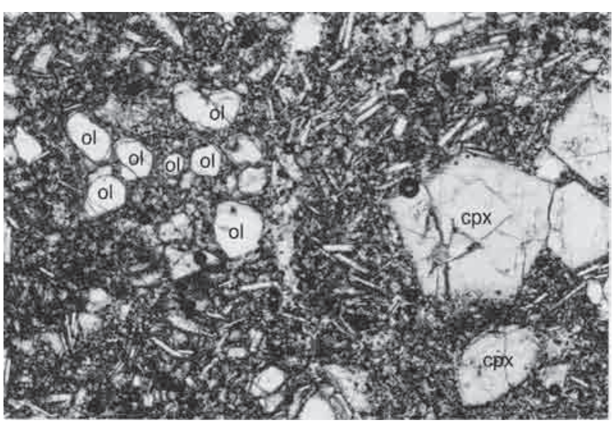

Figure 7. Photomicrograph of a porphyritic-aphanitic mafic rock. Clinopyroxene (cpx) and altered olivine (ol) phenocrysts are set in a fine matrix that contains thin laths of plagioclase. Plain polarized light; length of photo is 2.6 mm.

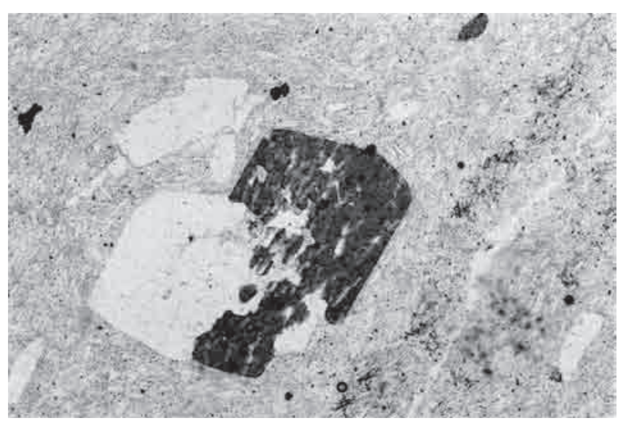

Figure 8. Photomicrograph of a porphyritic-aphanitic felsic rock. Plagioclase phenocrysts (white) and hornblende phenocryst (dark, intergrown with plagioclase) are set in a fine matrix of plagioclase laths that show flow structure. Plain polarized light; length of photo is 2.6 mm.

Figure 9. Photograph of a felsic rock composed of previously formed lens-shaped felsic rock. The lenses are parallel, imparting a strong flow structure to the rock, and within the lenses, on the microscopic scale, plagioclase laths show a strong flow structure parallel to the lengths of the lenses.

BRECCIAS

Three breccia bodies were found in the study area and two (breccia Number 1 and Number 2) were studied intensively. All three breccias were either surrounded by or in proximity to aphanitic rock. Breccias Number 1 and Number 3 are mafic-hosted while breccia Number 2 has felsic rock cropping out nearby. The precise dimensions of the breccia bodies were difficult to determine. Judging from its actual exposed area and topographic expression of the surrounding pastureland, breccia Number 1 appears circular in outcrop pattern and has a maximum diameter of approximately 45 meters. Breccia Number 2 forms along the crest of a small tree covered ridge and crops out in two patches, with a total long dimension of around 90 meters. Breccia Number 3 crops out for several meters along the bank of a stream and did not yield samples fresh enough for detailed study.

Breccia Number 1

Breccia body Number 1 crops out on the side of a small knoll where the pasture grass gives way to a black-brown rocky rubble and soil (Figure 10). This body is characterized by a chaotic assortment of angular to rounded xenoliths of mafic igneous and sedimentary country rock up to 15 cm in size. Single crystals (xenocrysts) are embedded in a fine powdery matrix with up to 70 percent of the rock composed of xenoliths and xenocrysts compared to matrix. Xenoliths that can be identified in the field include: red iron-stained aphanitic mafic rock, gray limestone, chips of shaly limestone, and earlier-formed breccia.

Thin sections of breccias are notoriously difficult to make. However, by means of a hand corer, fresh rock for thin sectioning was recovered. Thin section analysis reveals more details: xenoliths include both finer grained (0.1 mm) vesicular aphanitic plagioclase – clinopyroxene basalt and slightly coarser-grained (0.2 mm), non-vesicular aphanitic plagioclase-clinopyroxene basalt. Xenocrysts (augite, olivine, and rare hornblende) are commonly 1-2 mm in size and are bounded by both well-defined crystal faces and broken and fragmented surfaces. The matrix is highly altered, fine grained, and basically

Figure 10. Panoramic view of the field area looking northwest. The black patches in the center of the picture are the exposures of breccia body Number 1. Mafic rock dominates the area immediately surrounding the breccia to the line of grassy knolls that extends across the length of the photo just behind and uphill from the breccia. Running along the crest of the line of knolls is a northeast-trending felsic dike. The large ridge in the background is Monterey Mountain. Grazing cows provide scale.

indecipherable although there are areas of sheet silicate that resembles chlorite. Other areas appear composed of fibrous zeolite. Samples commonly contain numerous rounded vugs that are filled with carbonate or zeolite. Some of the vugs, judging from their shapes, are replaced xenocrysts or xenoliths.

By brushing the rubble away, it is possible to expose relatively fresh breccia and to observe its internal characteristics. In most places, the breccia appears utterly chaotic and unsorted. However, in a few places, a crudely developed size sorting is observed as a weak layering of coarser xenoliths (Figure 11) on the 4-10 cm scale. A N45°W strike and steep southwest dip angle of the layers in one spot is counter to the predominantly northeast strike of the bedding of the rocks of the surrounding bedrock.

Breccia Number 1 sits at the edge of a larger area of aphanitic mafic rock. The mafic rock consists of: aphanitic vuggy plagioclase-clinopyroxene basalt and porphyritic basalt with olivine, augite, and plagioclase phenocrysts. A unique feature of breccia Number 1 was the discovery of one xenolith composed of previously formed breccia (Figure 12). A thin section of the clast reveals that it differs from the usual breccia in that, while it contains single crystals of well-terminated 2-5 mm clinopyroxene with abundant vugs in a highly altered matrix, it lacks any xenoliths of any type that is normally found in other breccia (Figure 13).

Figure 12. Field close up of the previously formed breccia clast that was included in breccia body Number 1. The dark angular grains are clinopyroxene crystals, and the lighter rounded objects are vugs.

Figure 11. Outcrop photo of breccia body Number 1. Note the weakly developed beds of coarser clasts that occur below and above the quarter that is in the center of the photograph.

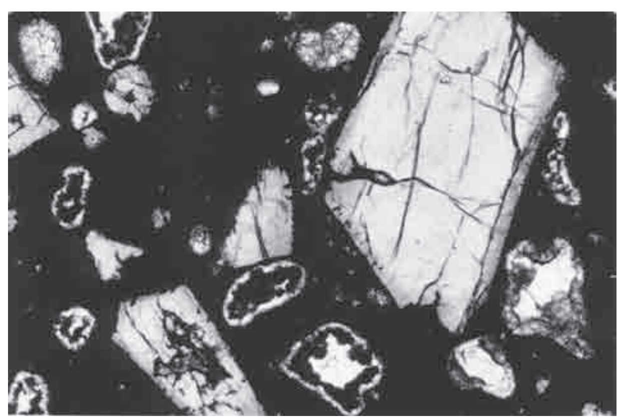

Figure 13. Photomicrograph of the "breccia within the breccia" clast of figure 12. The angular grains are clinopyroxene crystals and the rounded objects are empty vesicles or vugs filled with calcite or zeolite. The matrix is a fine, dark, and highly altered. There is a notable lack of xenoliths in this rock. Plain polarized light; length of photo is 2.6 mm.

Breccia Number 2

Breccia body Number 2 is found as a series of outcrops along the crest and side of a small ridge. The outcrop is relatively fresh and rings when struck with a hammer, a rarity for breccias. Interspersed with the breccia are outcrops of felsic rocks (no mafic rocks were found in the immediate area). Much of this body is located in woods and is lichen covered. This cover obscures much of the details of the internal structure and its relationship with the felsic rock. Texturally, it contains the same type of chaotic assemblage of xenoliths of igneous rocks and sedimentary country rocks, xenocrysts, and vugs seen at breccia Number 1. Unfortunately, due to lichen cover, we cannot definitely identify layering similar to breccia Number 1.

Thin sections of breccia Number 2 show it to have a greater variety of xenoliths and xenocrysts from multiple sources than breccia Number 1. Xenoliths identified in thin section include: carbonate, sandstone (subarkose), felsic igneous rock (both aphanitic and porphyritic-aphanitic with biotite and plagioclase phenocrysts, typically with a trachytic groundmass), and mafic igneous rock (matrix of plagioclase and augite, some porphyritic, some aphanitic, with phenocrysts of plagioclase, augite, and olivine). Xenocrysts are predominantly plagioclase (both euhedral and fragmental), clinopyroxene (both euhedral and fragmental), with smaller amounts of biotite, hornblende and rare olivine. What is interesting about the thin sections studied is that mafic xenoliths are more common than felsic xenoliths despite the fact that the diatreme is hosted by felsic rock and no mafic rock crops out in the immediate vicinity.

Breccia Number 2 reveals two additional features not observed at breccia Number 1. Irregularly shaped black glassy pods appear at the northern end of the body. The pods are up to 10 cm in length and appear folded into the breccia host. Additionally, in the same area, black shale xenoliths are found. The shale is found both within the breccia as 2-3 cm clasts and weathered out as chips in the soil overlying the diatreme. The lithology, color, and weathering characteristics of these chips do not resemble what is found in the surrounding Wills Creek or Tonoloway Formations but are more similar to younger shales within the Devonian rocks such as the Millboro Shale.

Breccia Formation

It is instructive to compare breccias found in the study area to breccias elsewhere. For a thorough review of this topic, the reader is referred to Mitchell, 1986. Breccia bodies such as those found in Highland County are the result of the erosion of "diatremes" (Figure 14). In profile, the breccia is contained within a pipe-like or funnel-shaped body that flares outward toward its top and tapers inward at depth. Erosion exposes a nearly horizontal cross-section, yielding the circular outcrop patterns seen in the study area. Diatremes are associated with igneous rocks of many different composition types from ultramafic to felsic.

Diatremes are perhaps best known for their association with diamond-bearing kimber-

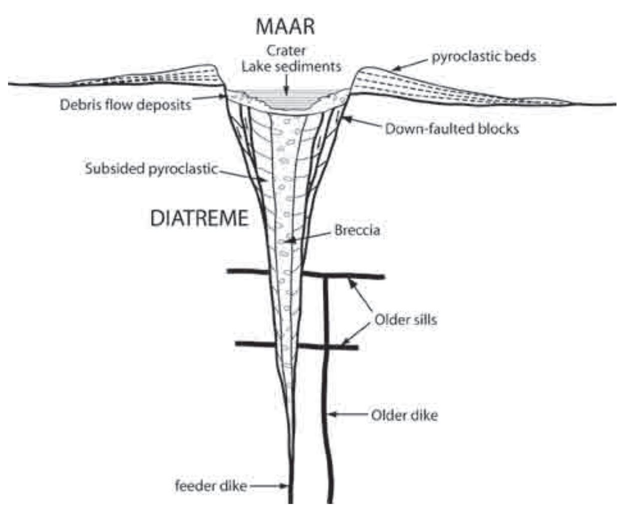

Figure 14. Sketch of a diatreme and overlying maar. Based on Mitchell, 1986, Lorenz, 1986, and Hearn, 1968.

lites such as those in South Africa and Russia. Deep mining of these kimberlite pipes has allowed geologists to form a three dimensional picture. Lengths of these pipes can reach a maximum of 2000-2500 m, while the diameter toward the top of the pipe can reach 1500 m. Below the diatreme pipe, the root zone is termed the "hypabyssal facies" where the rock type transitions from breccia into the igneous rock that is the crystallized remnant of the magma source. Many of these rocks are in the form of dikes that follow joints in the surrounding rock, while sills are controlled by resistant layers in the surrounding rock.

The tops of diatremes are rarely preserved because of erosion. What we know of this comes from relatively young eruptions. Cenozoic diatremes are found in the Eifel region of Germany in a 600 sq. km area that contains 240 volcanoes. A volcano type called a "maar" is observed at the ground surface above the diatremes. A maar is composed of a central collapse crater surrounded by a ring of pyroclastic beds that accumulates around the crater and thins rapidly outward (Lorenz, 1986). During eruption, rock fragments, volcanic ash, glass, and crystals become airborne and deposit many layers of material around the crater to form the ring-shaped sloping pile of material. The central crater serves as a topographic depression that may eventually fill with water to form a lake. In 1977, at Ukinrek, Alaska, a pair of maars formed during 12 days of eruption. The larger of the maars contains a crater 300 m wide, 70 m deep that is now filled with water forming a crater lake and has a mafic lava dome. During the height of the eruptions, ash clouds rose to a height of 6500 m, blocks were thrown as far as 600 m away, and light ash fell up to 160 km north of the eruption.

The dominant rock within the main part of the diatreme pipe is breccia. This rock is a jumble of rock blocks (xenoliths) of various sizes, single crystals (xenocrysts), glass, and fine volcanic ash. All this material, especially the fine matrix, may be highly hydrothermally altered, making original lithologies nearly unrecognizable. The xenoliths are principally of the country rock surrounding the pipe, and also of igneous rock that might either be from previously formed sills and dikes, or cooled from the magma responsible for the diatreme itself. Xenoliths may also come from the deep source area of the magma, such as the mantle or lower crust. Additionally, diatremes may contain xenoliths from rock formations higher in the stratigraphic section that has since been removed by erosion (Hearn, 1968). Many diatremes contain xenoliths that are quite angular, indicating an eruption style that violently shatters the walls of the pipe. However, many xenoliths are rounded, indicating abrasive action during the eruption and mixing of the material in the pipe.

The consensus of how diatremes form has evolved since they were first studied. Early theories called for an "explosive boring" method where pulses of magma from the mantle or lower crust rapidly rise through fractures, shattering their way until, at a critical depth where pressure reduces to low enough levels, dissolved gases in the magma (H_2O and CO_2) suddenly separate from the magma and violently blow out (Mitchell, 1986). The gas streams upward, mixing with rock in a process called "fluidization" forming an abrasive stream that "sandblasts" its way upward, enlarging conduits and forming much of the breccia in the pipe.

In the last several decades, the role of "hydrovolcanism" has become increasingly recognized as a key player in diatreme formation. In this theory, magma moves upward through joints until it reaches a rich source of groundwater. At the contact between the hot magma and cooler groundwater, the water violently flashes to steam, shattering the bedrock while incorporating some of the magma. The material is then expelled upward, breaching the ground and becoming airborne. The material falls around the crater to form a ring of tuff with a central crater. There are two points to emphasize: 1) the eruption lasts as long as there is an adequate supply of groundwater and not when magma runs out, and 2) the eruption initially begins at shallow depths (200-300 m). Shallow depths and low pressure are necessary in order for water vapor explosions to occur (Lorenz, 1986). Once the eruption gets going and as long as the water supply holds out, the crater propagates downward, using up the water and creating an increasingly deeper "cone of depression" in the groundwater table, thus allowing the pipe to deepen. As the pipe propagates downward, normal faulting occurs along the sides, thus allowing the pipe to widen while the sides collapse. The eruption style is both pyroclastic in nature and episodic. Thus, not only will ejected material form layers of tuff around the maar, it will also fall back into the crater itself, causing pyroclastic bedding within the pipe. Layered kimberlitic diatremes in western Montana that contain graded beds on the 1.2-30.5 cm scale have been described by Hearn (1968). As the diatreme moves downward into older bedrock, and as this material ejects out, older bedrock clasts will increasingly be found in the higher beds of tuff surrounding the maar. During the pauses between eruptions, the tuff forming the walls of the central depression may landslide back into the crater in the form of lahars. These lahar deposits may become interlayered with pyroclastic beds within the diatreme. Once the water supply is used up, the hydrovolcanic phase of the eruption ends and magmas may work their way up the pipe into the central crater to form lava flows.

Important to the hydrovolcanic model of diatreme formation is the fact that the process is relatively low temperature. Thus, diatremes do not show contact metamorphism of the country rock. The formation of the diatreme walls is predominantly one of collapse, not of outward explosion. Thus extensive faulting of the bedrock outside of the diatreme is not commonly observed. Within the diatreme, along the walls, concentric normal faults form as the sides collapse down. The extensive hydrothermal alteration of the breccia and zeolite growth in vugs attests to the role of water in the formation of diatremes.

DISCUSSION

The causes of what initially triggered igneous activity in the Eocene of Highland County is beyond the scope of this study. From field and thin section observation, however, we can place some limits on how the igneous activity occurred and what controlled its movement through the bedrock. Many of the features seen in diatremes elsewhere are also found in Highland County. Thus, by comparison, it is possible to gain insight on the eruptive style of the igneous rocks.

From joint data, field observation, and mapping, it appears that the dominant joint sets in the region provided the primary pathways for the ascent of both mafic and felsic magmas. Southworth and others, 1993, found that both mafic and felsic rocks yield age dates of about the same age (48 Ma), implying a genetic relationship between the two composition groups. The present study supports this idea, and an attempt was made to determine crosscutting relationships between the two types. Unfortunately, the study area did not reveal instances of mafic xenoliths in felsic rock and vice-versa. Northwest of breccia Number 1, a prominent line of felsic outcrops traces near the mafic body that surrounds breccia Number 1. However, vegetation and soil obscures the contact between the two. It should be noted that Rader and others, 1986, report that in a quarry near Hightown, Virginia, a mafic dike cuts a felsic dike.

Breccia bodies in the study area are always associated with other mafic and/or felsic rock. The prevalence of previously formed igneous xenoliths within the breccias suggests that the breccias formed later. This is in agreement with map patterns that suggest that the breccia bodies cut across the nearby mafic or felsic rock. This fits the hydrovolcanic diatreme emplacement model in the following way: dikes work upward through joints, and at some point, a dike approaches shallow depths where it intersects a source of water and begins the process of diatreme formation which then propagates downward into the deeper dikes. If the groundwater supply becomes cut off, later sills and dikes move up through and intersect the diatreme. This, however, was not observed in the study area.

Because the breccias appear to be later features, a study of their mineralogy can provide information on which magmas were powering them, and therefore which magmas erupted later. The key is to study the single crystals within the breccia. In diatremes, these crystals mainly come from two sources: as true phenocrysts from the original magma feeding the diatreme from below, meaning that the magma was a crystal plus liquid mush; and from previously solidified igneous xenoliths that became disaggregated during eruption, with the crystals separating out, forming the single crystals (or "xenocrysts") that can be seen embedded in the matrix. In breccia Number 2, the latter situation probably dominates. Thin sections of breccia Number 2 show instances of xenoliths separating into individual crystals (Figure 15). In addition, single crystals of biotite, hornblende, plagioclase, and clinopyroxene in the breccia are morphologically similar to those found in both felsic and mafic xenoliths within the breccia and that of the surrounding rock. Thus, it appears that the crystals in breccia Number 2 are derived from older rock, and none can be identified as phenocrysts from the feeding magma. This is a topic that requires further study, especially to determine if precisely determined chemical compositions of the crystals will provide clues to their origin. Also a chemical analysis of the glassy pods previously described at breccia Number 2 would help.

Breccia Number 1 is even more problematic. In most samples, single crystals of olivine and especially clinopyroxene are abundant. However, the mafic xenoliths in those samples lack similar phenocrysts, although porphyritic mafic rocks with olivine and clinopyroxene may be found in nearby rocks outside the diatreme. The "breccia-within-breccia" clast previously referred to in Figure 12 contains well-formed single crystals of clinopyroxene but lacks any xenoliths. Thus all the single crystals in breccia Number 1 may be found in mafic rocks nearby, but less commonly in the xenoliths (if present) contained in the breccia. Again, further study is necessary. It should be pointed out that Rader and others, 1986, interpret Trimble Knob to be a mafic diatreme body.

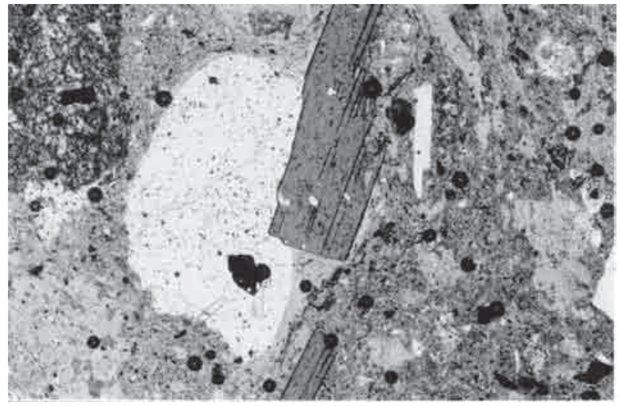

Figure 15. Photomicrograph from breccia Number 2 showing a rounded abraded plagioclase xenocryst with attached biotite that has not yet separated. Below is part of an already separated biotite. A mafic xenolith is found on the upper left corner. Other thin sections show various stages of phenocrysts separating out of xenoliths. Plain polarized light; length of photo is 2.6 mm.

Presumably, the mafic dikes, sills, and necks found in the region represent the underground plumbing that led to surface lava flows that have long since been eroded away. The diatreme pipes, by virtue of their ability to excavate their way downward, are the sole surviving volcano remnant.

How does the overall Cenozoic history of Virginia fit with Eocene volcanics? Since the breakup of Pangea and the opening of the Atlantic Ocean, the eroding Appalachians have left a record of sedimentation on the Atlantic continental shelf, slope, and rise (Poag and Sevon, 1989). Rapid erosion and thick depositional blankets of sediment can result from a combination of several factors: tectonic uplift, subsidence of the sedimentary basin, relatively dry or cold climate promoting mechanical weathering and creation of siliciclastic sandy gravelly sediment, and low sea level. Thick sediment is noted during the Early to Middle Jurassic, the mid-Early Cretaceous, and the late Cenozoic (Middle Miocene to present). The Eocene, however, was a time of unusually low sedimentation rates. Poag and Sevon envision the region as being tectonically quiet and low-lying. Climatic temperatures peaked in the Eocene, creating a tropical rainforest environment favoring chemical weathering. In addition, stream gradients were low and sea level stood quite high. The deep crustal unrest and resulting igneous activity in Highland and Pendleton Counties occurred during this very quiet backdrop. Lava flows and steam-powered maars erupted into the tropical forest over the period between 48 to 45 million years ago and then subsided.

Since the Eocene, and especially since the Middle Miocene, the erosional situation along the Atlantic coast has changed. Uplifting land and the onset of glaciation have combined to created the greatest deposition rates in the Atlantic basin since the Jurassic. The present sculpting of the mountain landscape was accomplished during this time starting 25 million years ago. How much rock has been removed? It is not known for certain how much has been lost in Highland County. Mathews, 1975, estimates that an average of 2000 m of rock has been eroded from the Appalachians during the Cenozoic. The breccias of Highland County provide clues. Among the xenoliths included in breccia Number 2 are black shale chips. These chips can be found both embedded in the breccia matrix and weathering out into the surrounding soil. The shale is nearly paper thin, non-calcareous, and closely resembles the Devonian Millboro Shale. The Millboro Shale is younger than the Wills Creek/Tonoloway Formations that surround breccia Number 2. One possible explanation for this is that the shale is from a lower thrust sheet deeper in the crust. This would require that there be a major subsurface thrust fault placing older rocks over the Millboro Shale. However, geologic cross-sections constructed through the region (Shumaker, 1985 and Kulander and Dean, 1986) show no obvious indication of such a fault under the field area. An alternate explanation lies in the nature of diatremes. Because they are collapse features, younger rocks from overlying formations can fall into the crater. Thus it is possible to preserve rocks in diatremes from formations that since been eroded away (Hearn, 1968). Kettran, 1970, reported a similar situation. In one of his breccia bodies he found a lower to middle Devonian pelecypod from a black shale xenolith that he identified as being from the "Marcellus Shale". He identified the rock surrounding the breccia as lowest Devonian "Keyser" or "Coeymans" Limestone, suggesting to him there was "at least 500 ft of vertical mixing". In breccia Number 2, a Millboro xenolith found in a breccia surrounded by the Tonoloway Formation would have fallen a minimum of 1100 ft (330 m) through the intervening stratigraphy to reach its present level. This, then, provides a minimum estimate as to how much overlying rock has been eroded away and is well within other erosion estimates.

SUMMARY

Detailed field mapping of the Eocene igneous rocks and surrounding bedrock near Monterey, Virginia, reveal that jointing helped guide the ascent of both mafic and felsic dikes though the country rock. Breccia bodies (diatremes) show many similarities common to other diatremes worldwide. The diatremes represent the collapse crater of maar-type volcanoes that existed in the Eocene. The breccias contain xenoliths of surrounding sedimentary bedrock, previously formed igneous rock, and single crystals which appear mostly to be the result of disaggregating older igneous rock. However, the breccias also include xenoliths from rocks that we interpret as belonging to younger sedi-

mentary formations that have since been eroded away. If so, one can estimate how much overlying bedrock has been eroded away. In the case of Millboro Shale xenoliths, at least 1100 ft (330 m) of rock has been removed.

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